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GEOMAGNETIC FIELD DISTORTION BY A SOLAR STREAM AS A MECHANISM FOR THE PRODUCTION OF POLAR AURORA AND ELECTROJETS

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SUMMARY

This paper describes a mechanism for charge separation in the geomagnetically trapped radiation which may account for some observed phenomena associated with the polar aurora and the electrojet current systems. The following development is proposed: given that there exist eastward or westward longitudinal gradients in the geomagnetic field resulting from distortion of the geomagnetic field by solar streams, if the trapped radiation is adiabatic in character, radial drift separation of positive and negative charged particles must occur. It follows that, for bounded or irregular distributions of plasma number density in such an adiabatic drift region, electric fields will arise. The origin of such electric fields will not arrest the drift separation of the charged particles, but will contribute to exponential growth of irregularities in the trapped-plasma density. An adiabatic acceleration mechanism is described, which is based on incorporating the electrostatic energy of the particle in the energy function for the particle. Direct consequences of polarization of the geomagnetically trapped radiation will be the polar electrojet current systems and the polar aurora.

CONTENTS

I. INTRODUCTION

In a letter to the editor of the J. Geophys. Research (Kern, 1961), the author suggested the possibility that solar-stream distortion of the geomagnetic field might lead to a situation in which charge separation occurs in trapped radiation, thus giving rise to polar-electrojet current systems. The physical basis for the mechanism suggested is adiabatic particle motion caused by eastward or westward directed geomagnetic field gradients. Such geomagnetic field gradients could be expected as a result of the interaction of the geomagnetic field, containing trapped plasma, and an enveloping ionized solar stream of comparatively low-energy particles.

Distortion of the geomagnetic field by ionized solar streams has been considered by many authors in relation to the occurrence of polar electrojet current systems and aurora. The magnetic-storm theories of Chapman and Ferraro (1931, 1932, 1940) and Martyn (1951) require such distortion. Modification of the geomagnetic field by diamagnetic trapped-particle moments and current systems has also been considered by Dessler and Parker (1959), Akasofu (1960) and others. Recent progress in the understanding of relationships between plasmas and magnetic fields has led to several pictures of the form of a solar-stream-distorted geomagnetic field (Johnson, 1960; Piddington, 1959, 1960; Parker, 1960).

The mechanism described in the author's recent letter (Kern, 1961) is similar in certain respects to that described by Martyn in his theory of magnetic storms and aurora (Martyn, 1951), based on Chapman and Ferraro's ring-current theory of magnetic storms (Chapman and Ferraro, 1931, 1932, 1940). Störmer (1955) presents the objections that Martyn's theory of a radially polarized ring current explains neither the very thin ray arcs

nor horseshoe-arc auroral forms. It will be shown that these objections can be overcome by examination of adiabatic particle motion in the presence of geomagnetic field gradients, particularly for a distorted geomagnetic field with east--west components of geomagnetic field gradients.

The present development follows earlier suggestions by Vestine (1960), Chamberlain, Kern, and Vestine (1960), Kern and Vestine (1961), and Kern (1961) regarding the possible interactions between the geomagnetic field and radiation trapped or otherwise guided by the geomagnetic field. The mechanism suggested here for charge separation, or polarization, in the trapped radiation introduces the possibility of reversal of polarization near midnight. Plasma instabilities in the trapped radiation ensure that the auroral forms observed will be enormously variable.

In order to simplify the discussion which follows, adiabatic invariants of particle motion are employed. These are: (1) the diamagnetic particle moment, μ; (2) the integral of the linear particle momentum along a field line between mirror points, J; and (3) the total particle energy, U. These quantities are given by the following relations

$$\mu = \frac{W_1}{B} = \frac{W}{B_m}$$

$$J = mv\int_{B_m}^{B_m^*} \left(1 - \frac{B}{B_m}\right)^{1/2} d\ell$$

$$U = \frac{1}{2} m v^2 + qV$$

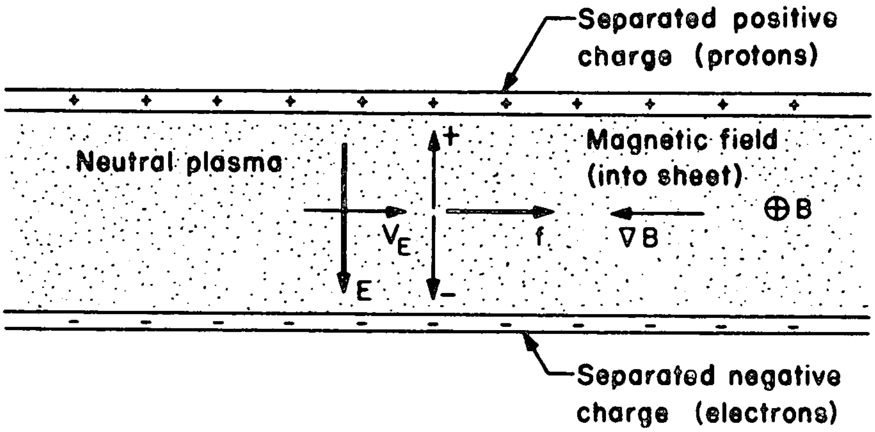
where W_1 is the transverse component of the particle's kinetic energy W, B is the magnitude of the geomagnetic field, B_m is the mirror-point field, v is the particle's total velocity, m is the particle mass, q is the particle's electric charge and V an electrostatic potential.

II. CHARGE SEPARATION AND POLARIZATION IN GEOMAGNETICALLY TRAPPED RADIATION

In the geomagnetically trapped radiation, two distinct types of adiabatic drift motion can be distinguished by applying the criterion of whether protons and electrons drift in the same or in opposite directions. $\underline{E} \times \underline{B}$ motor drift or any drift caused by forces which depend on the sign of electric charge of the affected particle will lead to adiabatic drift motion in the same direction for both positive and negative particles. Inertial forces or those dependent on magnetic moment will lead to adiabatic drift of protons and electrons in opposite directions.

Trapped radiation, being diamagnetic in character, will encounter a force in the direction opposite that of a magnetic field gradient. Proton drift motion due to an eastward or westward magnetic field gradient is given by $\underset{\sim}{V}_{dp} = (\mu_p/eB^2)\, \underset{\sim}{B} \times \nabla_\phi B$, where μ_p is the proton magnetic moment, e the electronic charge (here considered positive), $\underset{\sim}{B}$ the magnetic field, and $\nabla_\phi B$ the east—west component of the magnetic field gradient. A similar expression applies for an electron, but the direction of drift is opposite that of a proton, because of the opposite sign of the electric charge. Thus the total drift-separation velocity for two such particles is given by $\underset{\sim}{V}_d = \left[(\mu_p + \mu_e)\ /eB^2\right] \underset{\sim}{B} \times \nabla_\phi B$.

In a plasma with an irregular number density, this type of adiabatic drift will lead to charge separation, with associated electric fields. Figure 1 shows the result of charge separation due to transverse gradients in a magnetic field in a bounded slab of plasma. The geometry of this kind of charge separation, occurring in the geomagnetic field as the result of an eastward-directed geomagnetic field gradient, is shown in Figure 2. An electric field arises, directed from the separated proton sheet toward the



∇B: Magnetic field gradient, transverse to field giving rise to transverse force per particle $f = \mu \nabla B$

E: Electric field of separated positive and negative charge

V_E: Neutral $\underline{E} \times \underline{B}$ motor drift velocity due to electric field E

Fig. 1 — Charge separation in a bounded plasma due to transverse magnetic field gradient

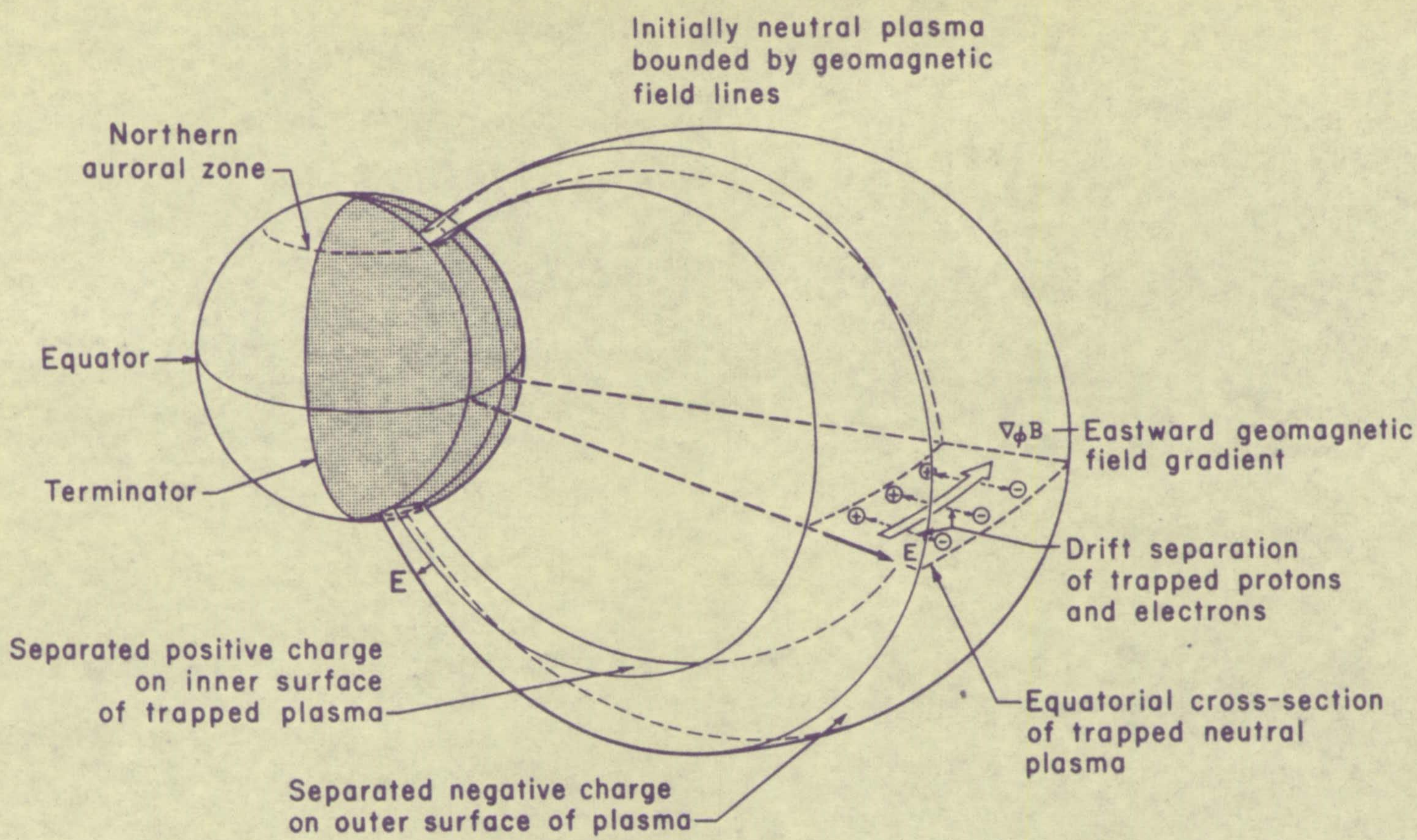


Fig. 2—Charge separation in geomagnetically trapped radiation due to eastward geomagnetic field gradient

electron sheet. It can be seen that such electric fields do not prevent or inhibit charge separation. On the contrary, $\underline{E} \times \underline{B}$ motor drift of the neutral plasma in the presence of such fields will contribute to the growth of any initial plasma-density irregularity and therefore lead to growth of polarization. The principles and methods for dealing with instabilities of this kind in inertial and other kinds of fields have been developed by Kruskal and Schwartzchild (1954) and by Rosenbluth and Longmire (1957).

Adiabatic charge separation due to geomagnetic field gradients is possible provided the system can supply the electrostatic potential energy associated with such charge separation. In the preceding paragraphs, the dependence of the charge-separation velocities on the diamagnetic moments of the particles was shown. This dependence, combined with the evident relation between the electric fields and the charge-separation velocities, suggests that growth of electrostatic potentials occurs at the expense of particle kinetic energies. Specifically, the energy of motion of the particles transverse to geomagnetic lines of force, which is directly related to the particle magnetic moments can be considered as a source for the energy associated with charge separation.

In an adiabatic system, the effects of electric forces transverse to field lines will be cancelled by equal and opposite Biot—Savart forces, or particles will undergo so-called $\underline{E} \times \underline{B}$ drift, unless local gradients exist in the electric field arising from excess charge. In the parallel sheet geometry suggested here, the effective electric force per particle in a sheet of excess charge can be simply related to the transverse particle velocity and the local number density of excess charge.

Adiabatic particle drift due to a transverse magnetic-field gradient which is antiparallel to the direction of such an electric force involves the expenditure of energy at the rate $\dot{W} = \underline{f} \cdot \underline{v}$, where $\underline{f}$ is the effective electric force per particle and $\underline{v}$ is the adiabatic drift arising from the transverse magnetic-field gradient. If the system is adiabatic, this energy must be supplied by the transverse kinetic energy of the particle, thus $\dot{W}_1 = - \underline{f} \cdot \underline{v}$, where $\dot{W}_1$ is the time rate of change of the particle's transverse kinetic energy. The effects of this transformation of kinetic energy into electrostatic energy will be discussed in the next section in which attention will be directed to mirror-point lowering in the trapped radiation.

Here the principal concern will be the examination of mechanisms leading from existing plasma irregularities to the observed phenomena of aurora and polar atmospheric-current systems. The charge-separation mechanism discussed above leads to a possible means of generating such phenomena, provided separated charge can precipitate into the atmosphere.

III. MIRROR-POINT LOWERING AND ADIABATIC PARTICLE MOTION IN POLARIZED TRAPPED RADIATION

It is apparent that processes for lowering mirror points of geomagnetically trapped radiation are of importance in promoting auroral displays and electrojets. The possible effects of solar-stream distortion of the geomagnetic field on trapped-radiation mirror points are discussed at some length by Vestine and Kern, (1961). In the following, two possible "dumping" mechanisms will be discussed which are associated with such distortion.

The first mechanism, mirror-point lowering by changing pitch angles through transformation of transverse kinetic energy to electrostatic potential energy, was suggested to the author by J. W. Chamberlain (private communication). A more complete treatment of this mechanism, which includes calculation of particle motion in regions of excess charge is given by Chamberlain (1961). Reduction of the transverse component of particle velocities discussed in the preceding section implies mirror-point lowering due to a reduction in diamagnetic particle moments, or alternatively, through reduction of the pitch angles of the particles. It will therefore be informative to examine the rates at which the transverse velocity of a particle varies with time in a region of excess charge of the same sign. Considering the two-dimensional geometry shown in Fig. 1, and assuming the existence of a uniform charge density n'e in the region adjacent to the boundary of the plasma sheet, it can be shown that the time average of the electric force per particle spiraling with transverse velocity v_1 in the ambient magnetic field is given by $2\pi c^2 e^2 n' \lambda_c$, where $\lambda_c = mv_1/Be$. Thus, for a particle undergoing adiabatic drift in a

transverse magnetic-field gradient, the time rate of change of the transverse kinetic energy is given by

$$\dot{W}_1 = + \left(\frac{\pi\ c^2 m^2}{B^3 r} \right) n' v_1^3\ \frac{dB}{d\phi} \quad .$$

Expanding $\dot{W}_1$, this equation can be solved for v_1 as a function of time t, assuming average values for the magnetic field B and the transverse component of the magnetic field gradient $(1/r)dB/d\phi$. The result is $v_1 = v_{10}\ [1 + \alpha v_{10}\ n't]^{-1}$, where $\alpha = (\pi m\ c^2/B^3 r)\ dB/d\phi$, and the other quantities have already been defined.

The time in which the transverse component of the velocity will decrease to 1/k times its original values is therefore $(1/\alpha v_{10}\ n')(k - 1)$. The characteristic time for decrease of the transverse velocity, therefore, is inversely proportional to the initial transverse velocity. This expression can be evaluated for 100-kev electrons. Taking $B_{av} = 10^{-3}$ gauss, $r = 5 \times 10^9$ cm, $e = 1.6 \times 10^{-20}$ emu, $c = 3 \times 10^{10}$ cm/sec and $dB/d\phi = 10^{-4}$ gauss /radian, α is approximately 5×10^{-11}. If v_{10} is taken as 10^{10} cm/sec, and n' taken nominally as $1/cm^3$, this gives the time for decrease to 1/2 the original transverse velocity as 2 seconds. For 1-kev electrons of about the same pitch angle, this time would be about 20 seconds. In a similar manner, the time required for a 50-fold decrease in transverse velocity would be of the order of 100 seconds for a 100-kev electron and 1000 seconds for a 1-kev electron. Thus for large changes in pitch angle, this process of lowering mirror points will be too slow to be effective in producing aurora. Lower separated-charge densities would yield still slower changes of transverse velocity for particles of any energy.

Another process of mirror-point lowering is associated with the generation of electrostatic fields in the trapped radiation. It has been noted that separated charge is less effective in altering the transverse kinetic energy of low-energy particles than of high-energy particles. It is apparent that the nearly two-dimensional geometry (see Fig. 2) considered here, effectively distributes electrostatic energy throughout particles traversing a region of separated charge. The effects of charge separation on low-energy particles in the trapped radiation will next be considered.

Acceleration of the linear motion of trapped particles can be viewed as the result of electric fields applied along geomagnetic field lines. Such electric fields will result from charge separation. Charged-particle acceleration can be regarded as the product of Coulomb forces between particles of like sign trapped on a given field line. If particle motion is nearly adiabatic in the trapped radiation, Coulomb forces can accelerate particles only along lines of force. Particle motion transverse to lines of force will undergo no acceleration. An approach has been used here which utilizes conservation of the adiabatic invariants of particle motion. This method provides information regarding changes in mirror-point height and equatorward drift of the field-line latitude of trapped particles (Chamberlain, Kern, and Vestine, 1960).

In the charge-separation case considered earlier, and shown in Fig. 1, separated charge of either sign has negative electrostatic potential energy with respect to the separated charge of the opposite sign. If the electrostatic potential energy, qV, added to a given particle by charge separation is negative, the total particle energy remains constant only when a corresponding increase in the kinetic energy of the particle takes place. This will

happen if the particle motion is adiabatic. The diamagnetic moment μ and linear-momentum integral J of a particle also remain unchanged in this type of particle motion. Conservation of diamagnetic moment can be used to compute mirror-point lowering as a result of increasing the kinetic energy of a particle (Chamberlain, et al, 1960). The mirror-point field can be computed from the relation $\mu = W/B_m$, where, for a given particle, μ is the diamagnetic moment, W is the kinetic energy (as modified by electrostatic potentials), and B_m is the mirror-point field of the particle. We obtain for the mirror-point field $B_m = W/_\mu$, where $W = W_o + qV$, W_o being the original kinetic energy and qV the electrostatic energy of the particle. The rate of change of B_m due to an increasing negative electrostatic potential V (with corresponding increase in kinetic energy) is $\dot{B}_m = (e/_\mu)\ \dot{V}$, where $\dot{B}_m$ and $\dot{V}$ are the time rates of change of B_m and V respectively. This rate can be written for the diamagnetic moment of any given particle. A schematic representation of mirror-point lowering by this mechanism is shown in Fig. 3.

A possible alternative to precipitation is that charged particles may travel up lines of force from the atmosphere to neutralize separated charge of the opposite sign in the trapped radiation. This might provide a mechanism for feeding the outer radiation belt from the atmosphere, rather than from solar streams. This type of "injection" mechanism would require priming by an initial supply of particles and would require, of course, the distortion of the geomagnetic field by a solar stream discussed above.

The number of particles that will be available for precipitation into the atmosphere will be the same as the charge excess due to charge separation in the region, since no charge separation can occur along lines of force.

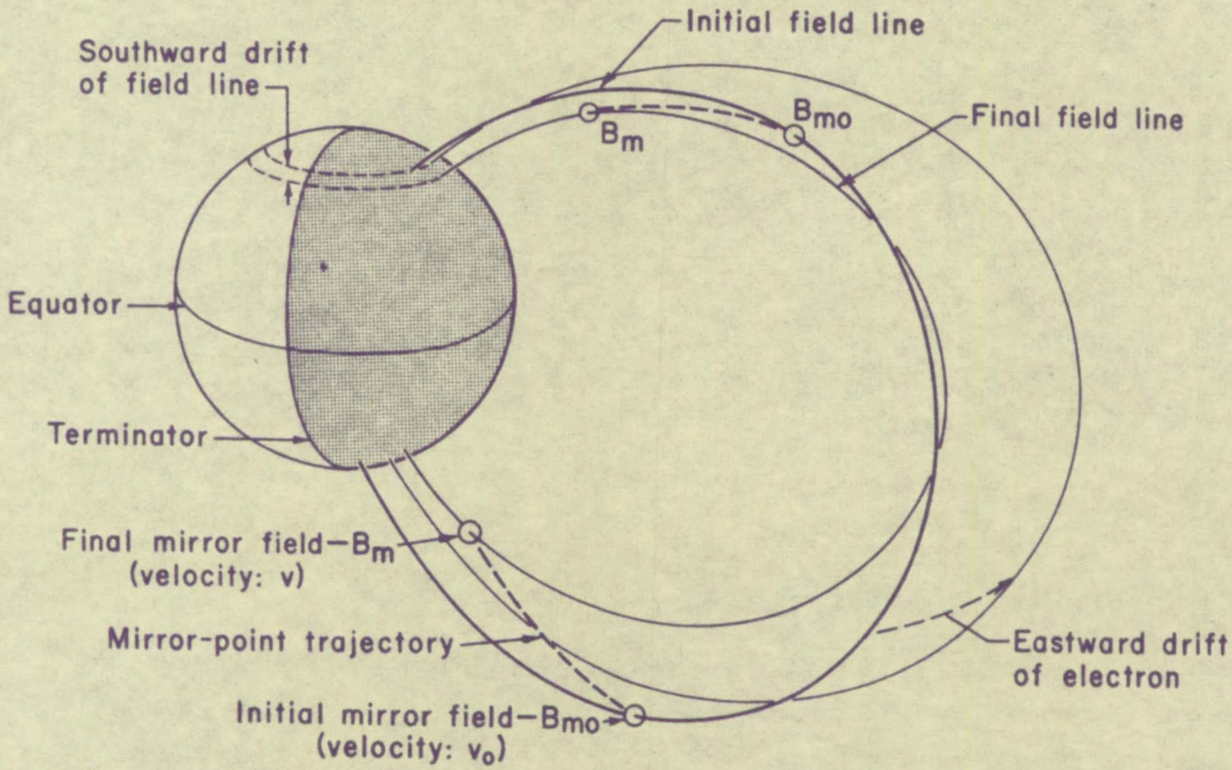


Fig. 3—Mirror point lowering and southward drift of an accelerated electron

Particles will be precipitated when the negative electrostatic energy over a given Störmer trajectory exceeds that necessary to depress the mirror points into the atmosphere. Thus two conditions must be satisfied for continuous discharge of particles to the atmosphere: (1) excess charge on a given field line, and (2) increasing negative electrostatic potential energy for a particle.

Acceleration of linear particle motion leads to drift of Störmer charged-particle orbits to shorter lines of force. To a first approximation, the drift of the particles to shorter field lines can be computed using the linear-momentum integral J over the geomagnetically constrained path between mirror points. Since this integral is invariant for slow changes in the field, a trapped particle undergoing an increase in total velocity v will move to a field line such that the linear-path integral $I = \int_{B_m}^{B_m^*} (1 - B/B_m)^{1/2} d\ell$ is reduced to keep the product vI = constant. This method of estimating the variation of mirror-point latitude has been used in a letter published earlier (Chamberlain, et al, 1960). Figure 3 shows the resultant motions of an accelerated electron: mirror-point lowering and equatorward drift, and eastward drift as in an undistorted field (Welch and Whitaker, 1959).

The inward drift to shorter field lines may explain the absence of auroral phenomena over the polar caps as being due to particle acceleration by eastward or westward geomagnetic field gradient components. Further, it may account for the decrease in counting rates observed by the Explorer VI satellite during the first stages of the magnetic storm of August 16-18 1959 (Arnoldy, et al, 1960) as the result of simultaneous acceleration and inward motion of the trapped radiation. A change in the energy spectrum of the geomagnetically trapped radiation would of course accompany such an

event, the effect being to harden the spectrum temporarily. Relaxation of solar-stream distortion of the geomagnetic field would lead to a return toward the original spectrum.

In order to investigate some of the effects of charge separation in geomagnetically trapped radiation, the behavior of a very simple system will next be considered.

IV. A SIMPLIFIED MODEL

If geomagnetic field line shells of equal linear-path integral, $I = \int_{B_m}^{B_m^*} (1 - B/B_m)^{1/2} d\ell$ are taken as surfaces of constant electrostatic potential, and the charge-separation mechanism described above is invoked, a simple model can be constructed for current flow and electric fields in the trapped radiation. Such a model is shown in Figure 4 (a), where a low-energy plasma of uniform number density is supposed to pervade the region connected by geomagnetic field lines to the auroral regions. It is also supposed that a discontinuous distribution of high-energy particles exists in this region. Figure 4 (a) shows hypothetical number densities of such high- and low-energy plasmas in the equatorial plane. Now, if distortion of the geomagnetic field by solar streams introduces longitudinal components of the magnetic-field gradients, forces depending on particle magnetic moments arise which lead to adiabatic drift separation of the protons and electrons. In this model, the low-energy plasma cannot be polarized since it is assumed unbounded and has a uniform number density. Separation of protons and electrons in the high-energy plasma will lead to increasing electric fields as the amount of separated charge increases.

Such electric fields will, of course, also affect the low-energy plasma, and will result in mirror-point lowering. The low-energy plasma will be much more strongly affected than the high-energy plasma; consequently, in regions of excess charge low-energy particles of like sign will be subject to possible discharge to the atmosphere.

Thus the high-energy plasma is subject to increasing polarization with consequent increasing electric fields (as indicated in figure 4 (b)). Discharge of low-energy particles to the atmosphere does not affect the

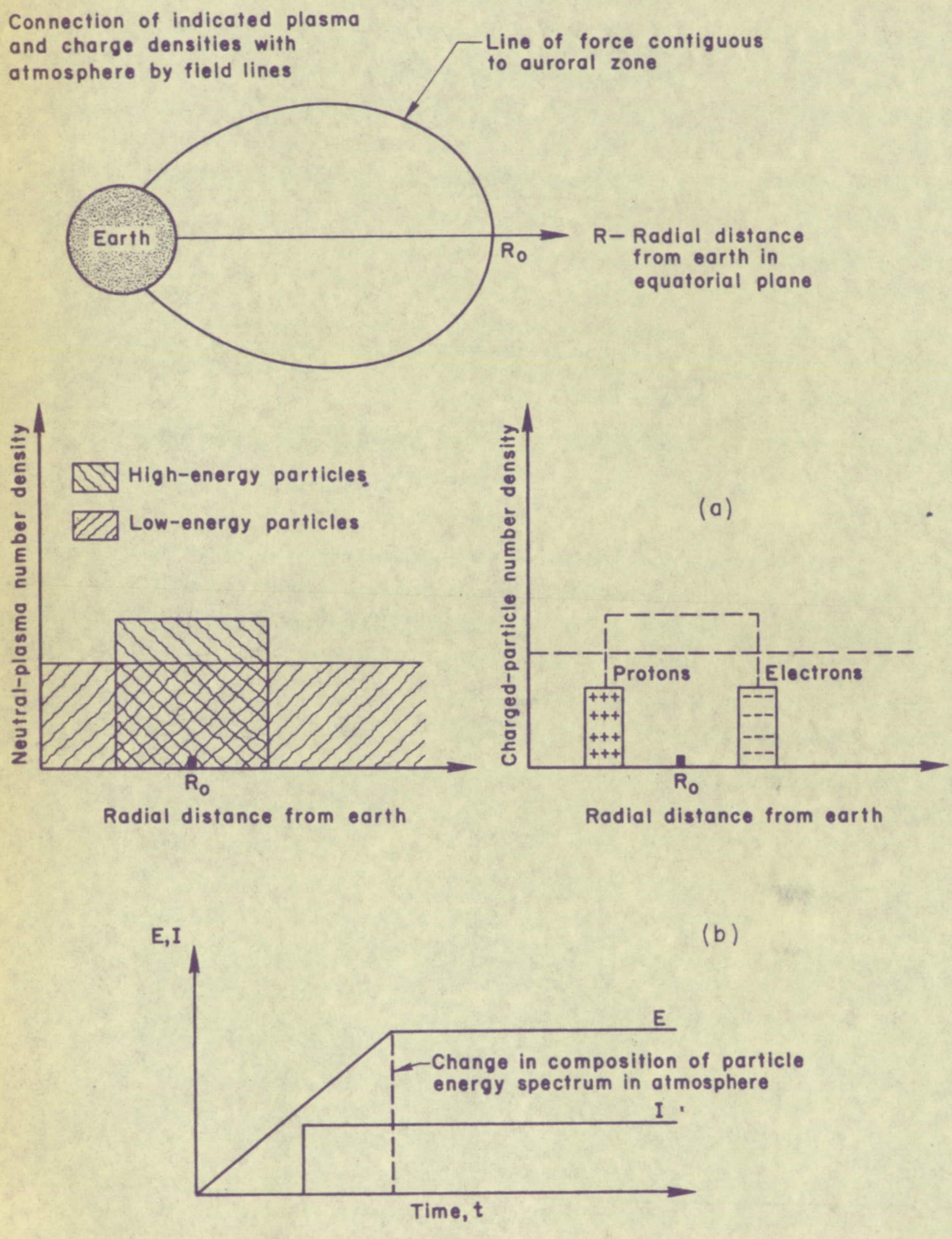


Fig. 4 — Model for electric field and atmospheric current resulting from charge separation

development of charge excesses in the high-energy plasma. The magnitude of the direct current observed in the highly conductive regions of the atmosphere depends on the rate at which excess charge becomes available. In the case considered here, this rate is constant; hence the low-energy particle current in the atmosphere will be constant. Figure 4 (b) shows the development of the electric field and the current in the atmosphere as a function of time. Note that the atmospheric current does not start immediately but begins following the development of the electric field to the value necessary to accelerate particles from the low-energy plasma into the conducting regions of the atmosphere. If the particle acceleration due to the electric field is sufficient to affect the mirror-point heights of the high-energy particles, conduction of these particles to the atmosphere will redistribute the high-energy plasma. This will lead to a change in the energy spectrum of particles incident in the auroral region.

V. POLAR ELECTROJET CURRENT SYSTEMS

If polar-electrojet current systems are ascribed to Hall conduction caused by meridional electric fields in the E-region (Baker and Martyn, 1953; Chamberlain, Kern and Vestine, 1960; Akasofu, private communication), eastward-directed electrojets are associated with poleward-directed electric fields and westward-directed electrojets with equatorward-directed electric fields. The drift directions produced by eastward-directed magnetic-field gradients are such as to produce poleward-directed electric fields, while westward-directed magnetic gradients produce equatorward-directed electric fields in the trapped radiation incident in auroral regions. Eastward-directed electrojets may therefore be associated with eastward-directed magnetic-field gradients, and westward-directed electrojets with westward-directed gradients (as in Figure 5).

The extent in longitude of such meridional electric fields would correspond to the extent of the eastward- or westward-directed magnetic-field gradients where irregularities in plasma density exist to allow the development of polarization. Electrojets would develop where sufficient trapped radiation, polarized and accelerated by the above mechanism, penetrates the ionosphere. A hypothetical distribution of eastward and westward components of the geomagnetic-field gradient is shown in Figure 6. Adiabatic drift of electrons before midnight in this model is northward to higher-altitude mirror points for a given mirror-point field; after midnight, the electron mirror points drift south to lower altitudes. The increase of ionospheric conductivity encountered by the electrons on penetration to lower altitude would seem to imply that polar electrojets due to Hall conduction will have greater intensity after midnight than for, say, a positive bay current system developing before midnight.

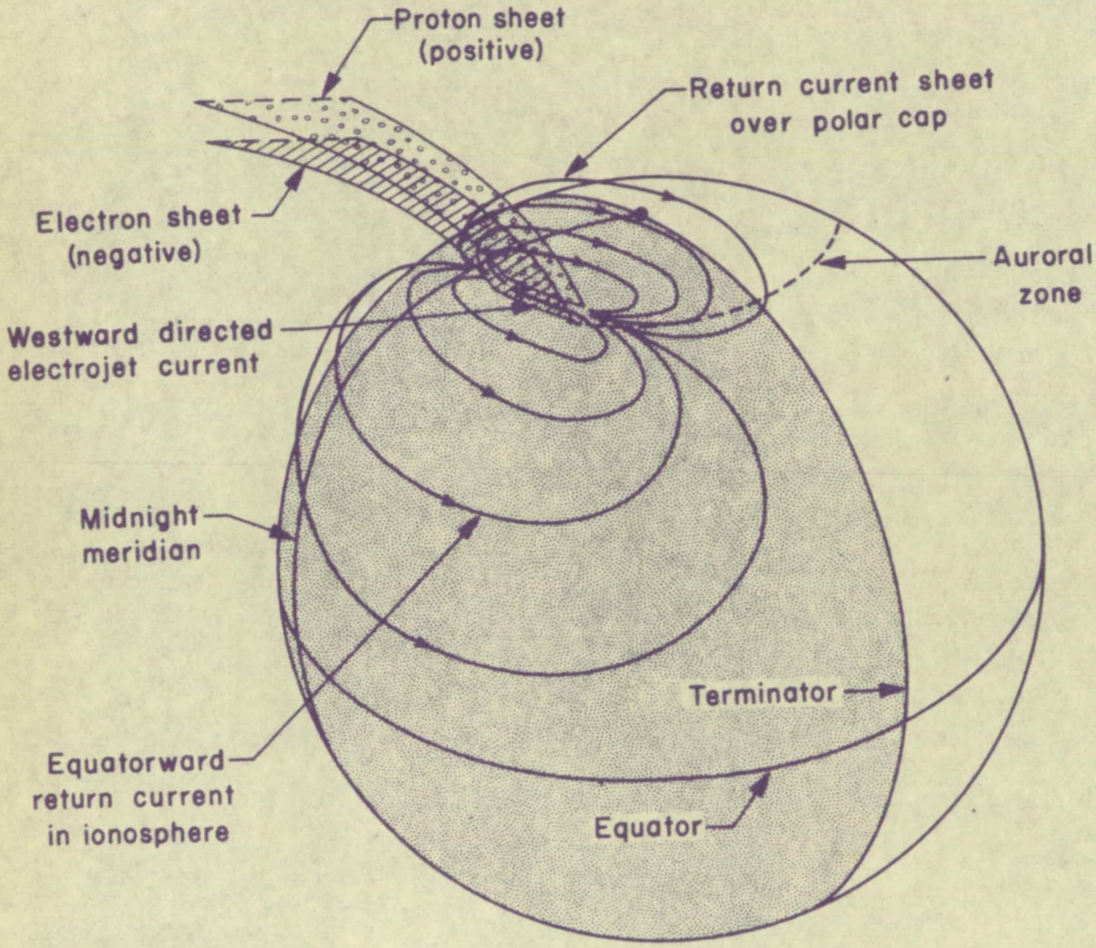


Fig. 5 — Polarization of radiation incident in the auroral zone and the Hall conduction polar electrojet currents

The process described above requires that the direct conduction current associated with the Hall-current electrojets be supplied by continuous charge separation in the trapped radiation. This current is equal therefore to the charge transport, $nev_d r \ell$ per radian of longitude contiguous to the auroral zone, where n is the plasma number density, $e = 1.6 \times 10^{-20}$ emu is the electronic charge, v_d is the separation velocity for particles of unlike sign, $r = 5 \times 10^9$ cm is the average radius of the region of drift separation conjugate to auroral latitudes, and $\ell = 2 \times 10^9$ cm is the approximate extent of the drift region along lines of force. The total direct conduction current per radian of longitude in the auroral region associated with a typical electrojet can be estimated. If Baker and Martyn's (1953) value for the height-integrated direct conductivity of 10^{-8} emu and an estimated electric field of 10^4 emu are used, and if the radius of the auroral zone is taken as 2.5×10^8 cm, this current turns out to be 2.5×10^4 emu per radian of longitude in the auroral zone. Equating this to the drift current given above, and taking $n = 10^3/cm^3$, permits calculation of the drift separation velocity required to maintain such a current as $v_d = 150$ cm/sec.

We can apply the equation developed earlier for the charged-particle separation velocity to obtain an estimate of the geomagnetic field distortion required to produce such drift velocities. For 6-Kev particles mirroring in the auroral region, the magnetic moment $\mu = 2 \times 10^{-8}$ emu. Since the magnitude of the longitudinal component of the magnetic field gradient can be written $\nabla_\phi B = (1/r)\, dB/d\phi$, we find that $dB/d\phi = (Ber/2\mu)v_d$. With $B = 10^{-3}$ gauss at 7 to 8 earth radii, $e = 1.6 \times 10^{-20}$ emu, $r = 5 \times 10^9$ cm, and $v_d = 150$ cm/sec, we obtain $dB/d\phi = 3 \times 10^{-4}$ gauss/radian. This amount of distortion is quite modest and would be considered applicable to times

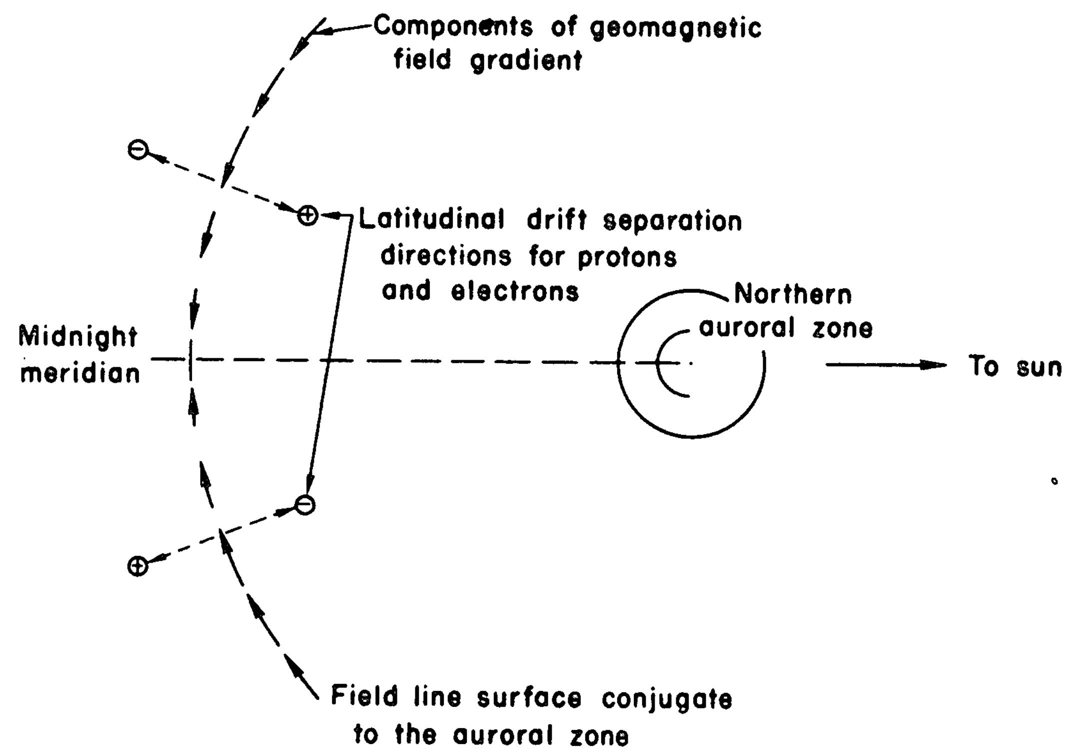


Fig. 6——Hypothetical eastward and westward components of geomagnetic field gradient

of magnetic bays. If particles of higher energy predominate, even smaller distortions could provide the necessary charge separation.

VI. THE POLAR AURORA

The implications of the mechanism described for auroral morphology are immediately apparent: (1) electrons incident at auroral latitudes will have kinetic energies which increase (in the mean) as a function of time, and (2) incident particle flux will be largest in auroral regions which are contiguous to the outer boundaries of the zone of trapped radiation. Particle-flux densities in the atmosphere will accordingly depend on (1) the charge separation velocity in the plasma contiguous to the region of incidence, (2) plasma density gradients in this region, and (3) the distribution of particle energies and magnetic moments within the plasma contiguous to the region of incidence.

The charge-separation mechanism outlined above has the feature of producing sheet beams of charged particles, and of maintaining such charge-density distributions in the trapped radiation (Kern and Vestine, 1961). If the region of geomagnetically trapped particles has a fairly sharp outer boundary contiguous to the auroral zone, the present theory suggests that west of (or prior to) local magnetic midnight an electron sheet will form on the outer boundary. After midnight, a proton sheet would be expected to form on the boundary. The charge separation leading to this pattern is shown in Figure 6.

The sheets of charged particles generated will be subject to electrodynamic instabilities as demonstrated both experimentally and theoretically (Khyl and Webster 1956; Pierce, 1956; Webster, 1955, 1957). Such considerations can be applied to auroral morphology with the result that the sequences of auroral forms can be ascribed to variations in

velocity and flux density of incident auroral particles (Kern and Vestine, 1961).

The systems of currents and the meridional electric fields associated with gradient components of the kind shown in Figure 6 are such as to account for the magnetic observations of Heppner (1954) for College, Alaska. Observed drift of auroral structures are accounted for in terms of $\underline{E} \times \underline{B}$ motor drift, westward drift being predicted before midnight and eastward after midnight (Nichols, 1957; Kim and Currie, 1958). Further, the observed southward drift of auroral structures (Leadabrand, et al, 1959; and others) can be identified with the predicted southward latitude drift of accelerated particles. The theory seems also to predict the drift of incident protons southward before and northward after midnight, as observed by Rees and Reid (1961).

Auroral morphology and drift directions of Davis (1960) are shown in Fig. 7. These distributions of auroral forms can be inferred from the combination of east-west charge separation derived from Störmer-orbit motion in the geomagnetic field and radial drift separation due to eastward or westward components of the geomagnetic-field gradient. The fixed spatial relation of the auroral pattern with respect to the sun observed by Davis (1960) would, of course, be predicted by this theory.

Heppner (1954) shows that auroral forms coinciding with peak westward-directed electrojets are often highly active rayed forms. Such forms would be consistent with the model developed above, in that they would coincide with peak electrostatic-field development in the

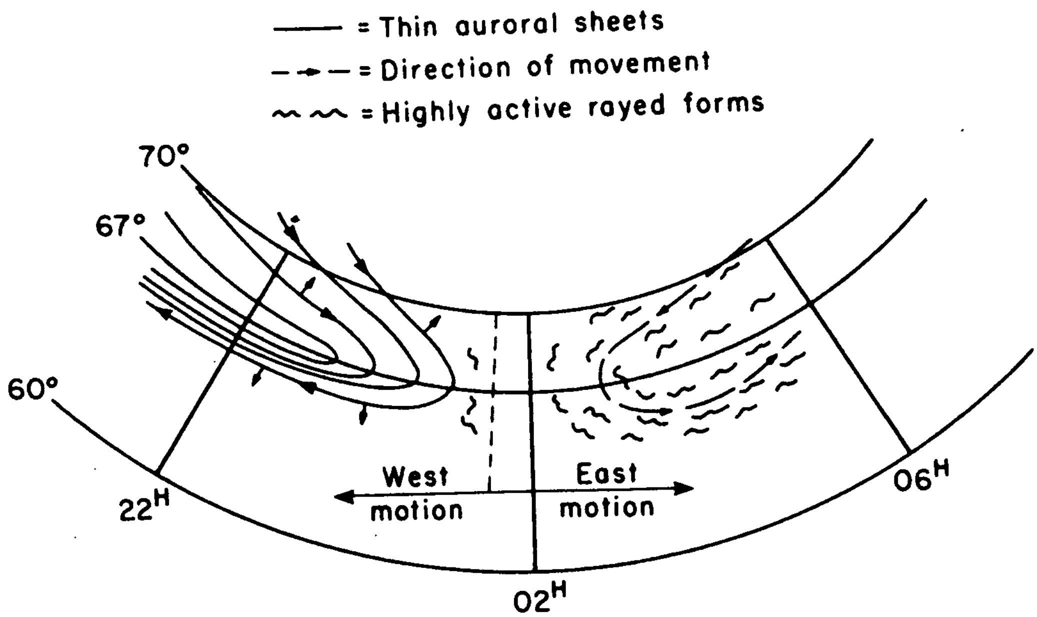


Fig. 7 —— Auroral morphology of Davis (1960)

trapped radiation. The high activity would be ascribed to electrodynamic instability arising from the characteristic behavior of beams of very energetic charged particles (Webster, 1957; Kern and Vestine, 1961). The peak electrojet current would be similarly associated with the highest electric field in the trapped radiation.

Rather sharp discontinuities in plasma density are required to generate auroral structures. The ad hoc assumption of such discontinuities in the neutral plasma contiguous with auroral regions is not untenable, since fluctuations in counting rates of satellites and probes passing through this region could be interpreted to indicate just such structure (Rosen, et al, 1960).

Direct evidence for the "dumping" of trapped radiation has been obtained through correlation of Explorer VII (1959 iota) radiation measurements with observations of visible and subvisible auroral emissions (O'Brien, Van Allen, Roach, and Gartlein, 1960). Their measurements also indicate that the radiation incident at lower latitudes is harder than that at higher latitudes, as would be anticipated in conjunction with the acceleration mechanism outlined here. That is, particles from a given region accelerated to higher velocities will be precipitated at lower latitudes. Additional evidence for the dumping and acceleration of trapped radiation has been obtained from analysis of satellite observations by Rothwell and McIlwain (1960).

VII. HORSESHOE AURORAL ARCS

Horseshoe auroral arcs can be derived as a consequence of charge separation operating on smaller irregularities in the neutral plasma which are longitudinally terminated in relatively steep plasma-density gradients. Steep plasma-density gradients in the east-west direction can lead to the development of horseshoe auroral arcs near magnetic midnight or wherever the predominant charge separation direction is east-west (as in an undistorted field, or where east-west field gradients vanish). Numerous so-called "horseshoe aurora" have been reported. Störmer (1955) shows two illustrations of this auroral form. Analyses of auroral observations have indicated that this auroral form is not rare, but is somewhat difficult to photograph. From elementary considerations, it can be shown that neutral plasma instabilities of the sort discussed above will lead to increased east-west number density gradients in any plasma irregularity. Observations available from probe and satellite counting rates indicate that sharp irregularities in the plasma number density do indeed exist (Rosen, et al, 1960).

Given such irregularities, it can be seen that adiabatic east-west particle drift will lead to charge separation. This situation is represented in an equatorial section in Fig. 8; the charge separation depicted leads to a charge density distribution that is horseshoe-shaped. Increasing electric fields will lead to precipitation of at least part of such a charge distribution in a horseshoe-shaped arc in the auroral zone.

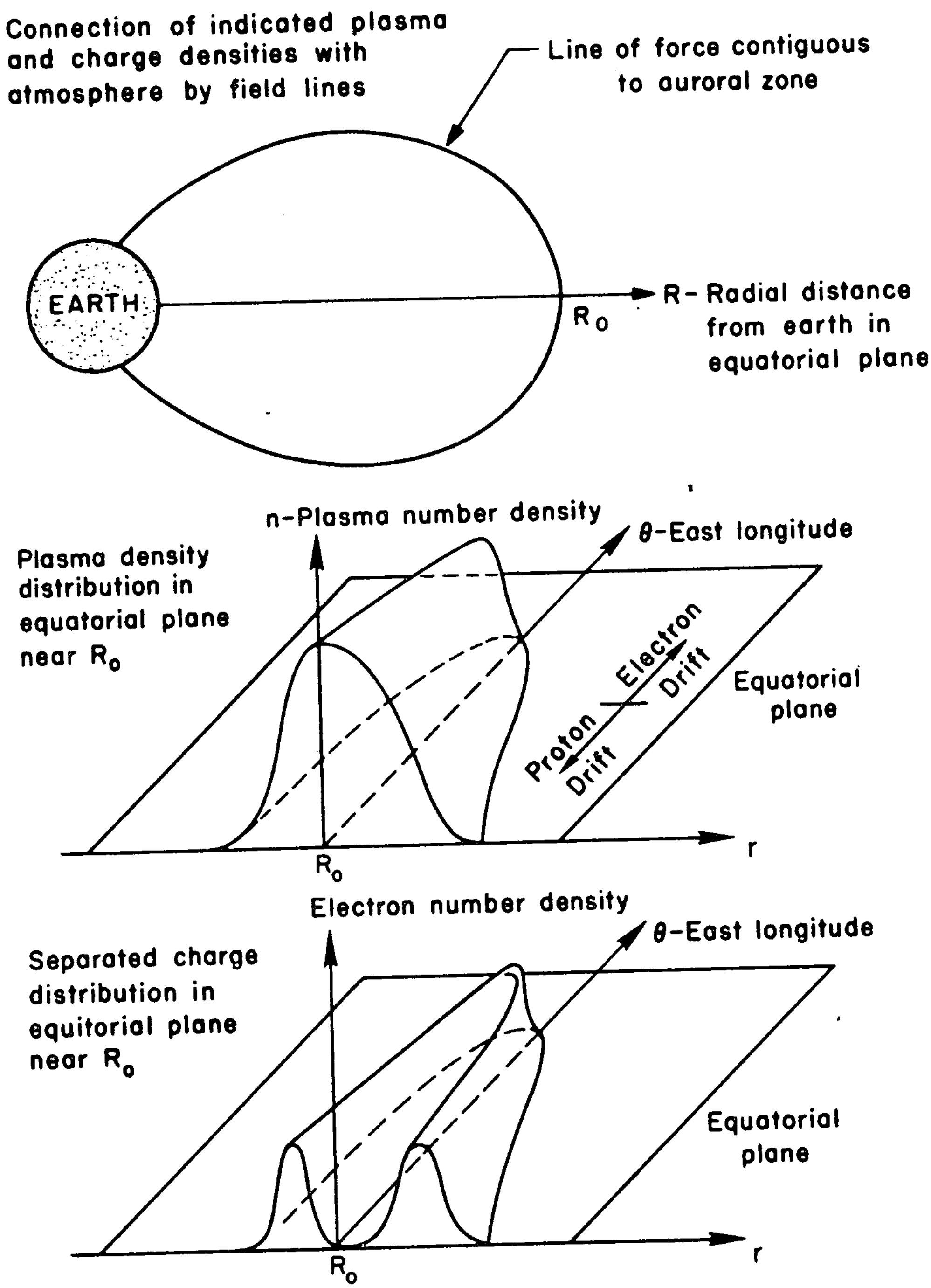


Fig. 8 — Charge separation leading to horseshoe auroral arcs

VIII. RECURRENCE OF POLAR AURORA AND ELECTROJETS

It has been shown that the polar aurora and electrojets may arise as a product of adiabatic particle motion in a geomagnetic field distorted by a solar stream. Recurrence of electrojets and aurora at about the same longitude on successive nights can be expected if there are low-energy particles in the trapped radiation contiguous to the auroral regions. Low-energy particles drift very slowly in longitude with respect to the earth's surface, and would effectively rotate with the geomagnetic field. Such a low-energy plasma would exhibit the pattern of adiabatic drift separation of charge imposed by solar-stream distortion of the geomagnetic field. Local sequences of polar aurora and electrojet phenomena can therefore be expected to reflect a 24-hour period corresponding to the rotation period of the geomagnetic field.

The theory presented here seems to account in some detail for the observed patterns of aurora and electrojet-current systems. The assumption that solar streams distort the geomagnetic field provides physical mechanisms leading to these phenomena. Such distortion has as yet been only inferred, and a complete analytic treatment of the problem has not yet been produced. If, however, the assumption is granted, then it would seem that the atmospheric phenomena of polar aurora and electrojets may provide some information regarding the nature of the solar-stream geomagnetic-field interaction. For example, the hypothetical east-west geomagnetic-field gradients proposed (see Figure 6) to account for the auroral morphology patterns of Davis (1960) indicate that dynamic pressure of solar streams may control the geo-

magnetic-field distribution near midnight. This pattern may, however, be better accounted for by hydromagnetic mechanisms.

If curvature of field lines is considered, the pattern proposed here would correspond to warping of field lines out of meridional planes toward the midnight meridian. Such warping might result if solar streams tend to extend lines of force on the night side of the magnetosphere.

Further exploration of the consequences of adiabatic particle motion will extend our knowledge of the behavior of trapped radiation. Extensive measurements of the particle-energy spectrum in the outer Van Allen belt are also necessary. A more satisfactory theory can be constructed when information of this kind becomes available.

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